Discovery Prospects for a Supernova Signature of Biogenic Origin

S. Bishop[a,1], R. Egli[b]

[a]*Physik Department E12, Technische Universität München, D-85748 Garching, Germany*
[b]*Department of Earth and Environmental Sciences, Ludwig-Maximilians University, Theresienstrasse 41, 80333 Munich, Germany*

Abstract

Approximately 2.8 Myr before the present our planet was subjected to the debris of a supernova explosion. The terrestrial proxy for this event was the discovery of *live* atoms of ^{60}Fe in a deep-sea ferromanganese crust. The signature for this supernova event should also reside in magnetite (Fe_3O_4) microfossils produced by magnetotactic bacteria extant at the time of the Earth-supernova interaction, provided the bacteria preferentially uptake iron from fine-grained iron oxides and ferric hydroxides. Using estimates for the terrestrial supernova ^{60}Fe flux, combined with our empirically derived microfossil concentrations in a deep-sea drill core, we deduce a conservative estimate of the ^{60}Fe fraction as ^{60}Fe/Fe $\approx 3.6 \times 10^{-15}$. This value sits comfortably within the sensitivity limit of present accelerator mass spectrometry capabilities. The implication is that a biogenic signature of this cosmic event is detectable in the Earth's fossil record.

Keywords: Earth; Geophysics; Geological processes; Mineralogy

1. Introduction

Cosmic production sites for ^{60}Fe are massive stars which produce ^{60}Fe during their quiescent helium- and carbon-shell burning phases [1, 2], followed by subsequent shock heating of their helium and carbon shells during the core collapse stage of their evolution [1–3]. Carbon deflagration Type Ia supernovae are another potential site for ^{60}Fe production [4, 5]. Both sites can produce up to 10^{-4} $M_\odot$ of ^{60}Fe. Radioactive ^{60}Fe, with a newly revised half-life of 2.62 Myr [6], has a β-decay scheme [6] that gives rise to two gamma-rays, from the decay of excited states in ^{60}Ni, with energies, $E_{\gamma_1} = 1173$ keV and $E_{\gamma_2} = 1332$ keV. It is an important radionuclide for tracing active nucleosynthesis within our galaxy because its half-life is much shorter than stellar lifetimes, yet also long as compared to the expansion time scales of supernovae ejecta thereby allowing sufficient amounts of it to survive the opaque ejecta phase and be susceptible to observation with gamma-ray astronomy. Recent gamma-ray astronomy studies have detected these gamma-rays within the inner radiant portion of the galactic plane [7], known to be a site of massive stars.

Using the accelerator mass spectrometry (AMS) facility [8, 9] of the Maier-Leibnitz-Laboratory, operated by the Munich universities, a concentration spike of *live* ^{60}Fe atoms was discovered [10, 11] in a Pacific Ocean deep-sea ferromanganese crust (FMC). The measured ^{60}Fe atom concentration was ^{60}Fe/Fe $\approx 2 \times 10^{-15}$. From these data, it was concluded that our planet has been exposed to the debris of a supernova (SN) ≈ 2.8 Myr before the present [11]. This interpretation was subsequently challenged [12] on the basis of highly variable FMC ^{3}He concentrations within the SN epoch. The variation in the ^{3}He concentration was attributed to the sampling of micrometeorites trapped in the FMC. The challenge thus made was that the discovered ^{60}Fe was of cosmogenic origin, produced by galactic cosmic ray spallation reactions on nickel within the micrometeorites. This challenge was subsequently refuted on quantitative grounds using the nickel and iron abundances of the FMC itself [13] and finding the identical ^{60}Fe/Fe signal in a different region of the original FMC [13] and, additionally, finding this same signal in a different FMC (29DR-32) obtained from the northern Pacific Ocean [14]. We are, ourselves, thus inclined to discount the micrometeorite hypothesis and consider a new ^{60}Fe reservoir.

The new terrestrial reservoir we propose are microfossils comprised of single-domain crystals of magnetite (Fe_3O_4), produced by magnetotactic bacteria extant with this SN event.

Provided these bacteria preferentially uptake iron from fine-grained iron oxides and ferric hydroxides, these microfossils should contain a biogenic signature of this SN event. We have characterized the iron mass concentration within the microfossils of a Pacific Ocean deep-sea drill core contemporaneous with the SN event. In contrast with a previous ^{60}Fe search in a sediment drill core extracted from the Norwegian Sea that found no detectable ^{60}Fe signal [13], we deduce that these microfossils should contain ^{60}Fe/Fe concentrations within the sensitivity limits of AMS and, moreover, that there is sufficient quantity of microfossils in our drill core to perform the AMS measurements.

2. Magnetofossil Reservoir

Magnetotactic bacteria are single cell eukaryotes that are are unique in that they produce intracellular crystal chains of single-domain (SD) magnetite (Fe_3O_4) crystals called *magnetosomes* [15]. Putative fossil magnetosomes (magnetofossils) have been dated as far back as 1.9 Gyr before the present [16].

Supernova iron arriving in the Earth's atmosphere in atomic/molecular form, or in the form of nanometer-sized oxides, is expected to rapidly react in aqueous environments via dissolution, binding to organic ligands, and re-precipitation in the form of poorly crystalline ferric hydroxides (FHO) [17]. In this form, Fe has a very short residence time of < 100 yr [18] in the global ocean system and finally becomes incorporated into the sediment by settling, or through chemical reactions involving the dissolved form such as with ferromanganese crusts. Organic complexes, FHO, and iron oxide nanoparticles incorporated into the sediment are easily dissolved and reprecipitated through sedimentary redox reactions. Specialized classes of bacteria actively drive the iron redox cycle by reducing available Fe(III) to Fe(II), which is then incorporated into new minerals such as magnetite (Fe_3O_4) and greigite (Fe_3S_4). Among these are the dissimilatory metal reducing bacteria (DMRB), which extracellularly induce the precipitation of secondary iron minerals such as siderite (Fe_3CO_3) and magnetite [19]; while magnetotactic bacteria intracellularly grow magnetite or greigite crystals [20]. From culture studies, such DMRB have been shown to preferentially utilize fine-grained iron oxides and ferric hydroxides as their iron source over the bulk-sized secondary minerals [21, 22]. This implies that those particles of high surface to volume ratios (i.e. the fine-grained nanometer-sized grains) are preferentially uptaken by these bacteria. In particular, surface normalized bacterial Fe-reducing reaction rates are $\approx 1.5 - 2$ orders faster [22] for nano-sized ferrihydrite particles as compared to grains with sizes comparable to bulk detrital grains. Assuming these findings also hold for magnetotactic bacteria, it is plausible that Fe processed by such bacteria almost entirely comes from the Fe pool of easily available forms, which would include the fine SN ^{60}Fe-bearing grains, with little addition of stable Fe from in-situ weathering of Fe-bearing primary minerals. Because isotopic fractionation effects are negligible, the isotopic composition of this Fe pool would then be reflected in the Fe isotopic composition of the magnetosomes. It is therefore reasonable to consider that those bacteria extant during the exposure of the Earth to the SN-ejecta took up ^{60}Fe and incorporated it into their magnetosomes, thus recording the signature of this event in the biological record of our planet.

3. Discovery Potential of Supernova ^{60}Fe in Fossil Magnetosomes

Because AMS makes a measurement of an atom ratio, the discovery potential of ^{60}Fe in fossil magnetosomes hinges on not only the incident flux of ^{60}Fe arriving on Earth, but also on the degree to which the ^{60}Fe is diluted in sedimentary marine reservoirs by influxes of stable Fe from the terrestrial iron-cycle. We have seen that ^{60}Fe can be incorporated into secondary minerals produced by DMRB or abiogenically during sediment diagenesis, such as with ferromanganese crusts. In like manner, terrestrial Fe is rendered to the sediment by these same mechanisms and, additionally, by way of minerals sufficiently large and chemically resistant to remain unaltered and, thus, survive diagenesis. Iron in primary minerals is exclusively of terrestrial origin, while all secondary minerals, whose formation was coeval with the SN event, will contain both ^{60}Fe and terrestrial Fe. Thus, those sediments having had conditions conducive for the support of magnetotactic bacteria and the Fe redox cycle, while having minimal detrital inputs, are best suited for detecting a SN event.

As a demonstrative example we discuss the case of an Ocean Drilling Project sediment core (ODP core 848, Leg 138), from the Eastern Equatorial Pacific (2°59.6′ S, 110°29′ W, 3.87 km water depth), focusing on the 2.4 – 3.3 Myr age interval corresponding to the SN event reported in Knie et al. [11]. The sediment is a pelagic carbonate (60 – 80% $CaCO_3$, 20 – 30% SiO_2) with a total iron content of 1.5 – 3.5 wt% [23]. The core-depth

age correlation was established by comparison of the Earth's magnetic field direction, as recorded by magnetic minerals in the sediment, with a reference polarity time scale [24]. The mean sedimentation rate of core 848 for the 2.4 – 3.3 Myr age interval is 0.54 cm/kyr [25]. The location of this core, being far removed from continental landmasses, should minimize detrital Fe inputs from coastal runoff.

The concentration of magnetofossils in this sediment core can be estimated by measuring two types of remanent magnetizations acquired in the laboratory: a so-called isothermal remanent magnetization (IRM), acquired in a 0.1 T field; and an anhysteretic remanent magnetization (ARM), acquired in a slowly decaying alternating field with an initial amplitude of 0.1 T superimposed on a 0.1 mT field of constant bias. The magnetic moments imparted by both magnetizations to $\approx$ 5 g samples of powdered sediment were measured in a 2G superconducting rock magnetometer. The IRM measurements are shown in panel (a) of Fig. 1 as a function of sediment age. While an IRM records the remanent magnetization of all ferrimagnetic minerals in the sample, regardless of their domain state, ARM is predominantly acquired by single-domain (SD) ferrimagnetic grains, or linear chains of such grains, that are well dispersed in a non-magnetic matrix [26]; therefore, the ratio between ARM susceptibility χ_{ARM} (ARM normalized by the bias field) to IRM, χ_{ARM}/IRM, is a sensitive domain state indicator that can be used to discriminate between primary and secondary ferrimagnetic minerals based on the large difference in typical grain sizes between the two types. Panel (b) of Fig. 1 shows our measured χ_{ARM}/IRM values as a function of sediment age. Well dispersed SD particles are characterized by χ_{ARM}/IRM $> 10^{-3}$ m/A, while for most primary minerals χ_{ARM}/IRM $< 2 \times 10^{-4}$ m/A. The SD particles produced by DMRB, which themselves would also contain ^{60}Fe, are expected to yield χ_{ARM}/IRM $\approx 2 \times 10^{-4}$ m/A [27] provided the value measured on a cell culture [27] can be extrapolated to natural conditions. Intact magnetosome chains are known, however, to have the highest reported values of $3^{+2}_{-1} \times 10^{-3}$ m/A [27, 28]. Our drill core sediment has values, shown in panel b) of Fig. 1, consistent with that expected for intact magnetosomes. We therefore conclude that the IRM of this core section is almost entirely carried by secondary SD minerals with a high proportion of magnetofossils. Further evidence for the predominance of magnetofossils as the primary magnetic remanence carriers in this core section is also provided by more specific measurements (not shown here) which fulfill the detection criteria stated in Egli et al. [29]
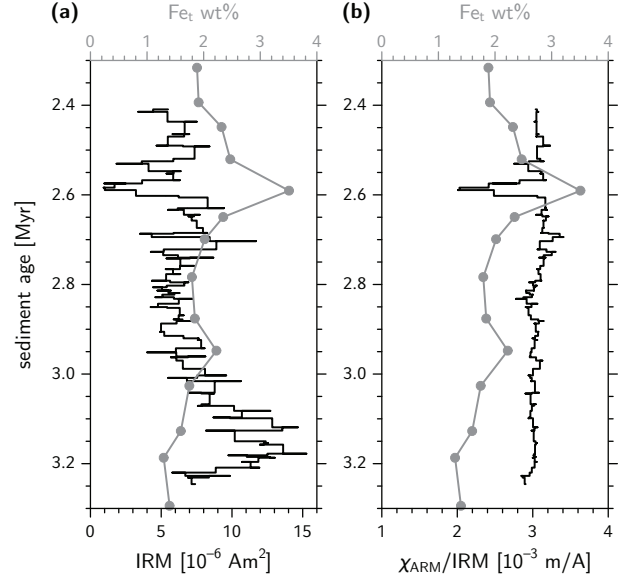

Figure 1: IRM and χ_{ARM}/IRM results from $\approx$ 5 g samples as a function of sediment age in ODP drill core 848, Leg 138. Panel (a) shows our IRM results, while panel (b) shows our χ_{ARM}/IRM results. The grey data points display the known iron percentage and are to be read from the top horizontal axis.

These IRM data in combination with the estimated supernova ^{60}Fe fluence determined in Knie et al. [11] permit an estimate of the ^{60}Fe/Fe ratio in this core section under the reasonable assumption that the measurements shown in Fig. 1 are representative of well dispersed SD magnetite. Since the switching fields of secondary ferrimagnetic minerals are smaller than the 0.1 T field employed to magnetize our sediment samples, the IRM corresponds to a saturation remanent magnetization, which, for non-interacting, uniaxial SD particles, corresponds to half the saturation magnetization.

The iron concentration C_{SDFe} contained in SD magnetite from this core can be estimated by way of,

$$C_{\mathrm{SDFe}} = \frac{2m_{\mathrm{rs}}}{w\mu_s} \frac{M_{\mathrm{Fe}}}{M_{\mathrm{Fe_3O_4}}} \qquad (1)$$

where m_{rs} and μ_s are the IRM-determined magnetic moment and saturation magnetization, respectively, of the magnetic mineral, w is the IRM sample mass, and M is the atomic mass of iron or magnetite as implied by the corresponding subscript label. From panel (a) of Fig. 1, an average value of $m_{\mathrm{rs}} \approx 6 \times 10^{-6}$ Am^2 is taken over the entire age span. The saturation magnetization of magnetite is $\mu_s = 92$ Am^2/kg, and the mass of each measured core sample was $w \approx 5$ g. These numbers yield an estimated single domain iron mass concentration

of $C_{\text{SDFe}} \approx 1.9 \times 10^{-5}$ g/g.

The corresponding flux of SD Fe in this core sample is determined by

$$\Phi_{\text{Fe}} = C_{\text{SDFe}} \frac{N_A}{M_{\text{Fe}}} \rho \frac{dh}{dt} \qquad (2)$$

where N_A is Avogadro's constant, while ρ and dh/dt are, respectively, the estimated density and sedimentation rate of the core material. We take $\rho \approx 2.7$ g/cm^3, consistent with that of calcium carbonate, along with the known sedimentation rate [25] $dh/dt = 0.54$ cm/kyr. With these numbers, Eq. 2 yields $\Phi_{\text{Fe}} \approx 2.9 \times 10^{17}$ atom/cm^{2}kyr in SD magnetite.

From the work of Ref. Knie et al. [11], the estimated ^{60}Fe terrestrial fluence, ϕ_{60}, after correcting for the new ^{60}Fe half life, is given by,

$$\phi_{60} = \frac{2^{\left(1/t_{1/2} - 1/t'_{1/2}\right)t}}{U_{\text{Fe}}} \phi'_{60} = 2.8 \times 10^8 \text{ atom/cm}^2 \,, \qquad (3)$$

where $t = 2.8$ Myr is the nominal time of the SN event, $t'_{1/2} = 1.5$ Myr is the old ^{60}Fe half life, $t_{1/2} = 2.62$ Myr is the revised ^{60}Fe half life [6], $U_{\text{Fe}} = 0.6\%$ is the Fe-uptake factor [11] of the FMC, and $\phi'_{60} = 2.9 \times 10^6$ atom/cm^2 is the FMC ^{60}Fe fluence measured by Knie et al. [11]. The width of the ^{60}Fe/Fe concentration spike of Fig. 1 in Knie et al. [11] suggests a characteristic exposure time, τ, of Earth to this fluence of $\tau \approx 500$ kyr, assuming that the residence time of iron in the ocean (< 100 yr) [18] is short compared to the exposure time. With these, the terrestrial flux of supernova ^{60}Fe is estimated using

$$\Phi_{60} = \frac{\phi_{60}}{\tau} \,. \qquad (4)$$

Although we have adopted the width of the spike as the characteristic exposure time, it is possible that this value could be much shorter ($\tau \approx 10$ kyr) [30]. However, as Eq. 4 shows, a shorter exposure time can only serve to increase the value of our flux; we therefore use the nominal value of $\tau \approx 500$ kyr for our prospect estimates.

Under the assumption stated in Section 2 that the bacteria will preferentially utilize the fine-grained iron-oxides and ferric hydroxides as their source of iron from which they construct their magnetosomes, an estimate of the resulting ^{60}Fe/Fe ratios contained in the magnetofossils is obtained by taking the ratio of Eq. 4 with Eq. 2.

Table 1 shows the resulting estimated ^{60}Fe/Fe ratios for three values of exposure time τ (250, 500 and 750 kyr) and for two different terrestrial supernova ^{60}Fe fluences: $\phi_{60} = 2.8 \times$

	^{60}Fe/Fe		
	$\tau = 250$ kyr	$\tau = 500$ kyr	$\tau = 750$ kyr
ϕ_{60}	1.8×10^{-12}	9.0×10^{-13}	6.0×10^{-13}
$U_{\text{Fe}} \times \phi_{60}$	1.1×10^{-14}	5.4×10^{-15}	3.6×10^{-15}

Table 1: Estimated ^{60}Fe/Fe ratios in single domain magnetite in Site 848 drill core for different SN-ejecta exposure times and two ^{60}Fe fluences.

10^8 atom/cm^2 as described above in Eq. 3, and the more conservative case of $U_{\text{Fe}} \times \phi_{60}$. This conservative case is also considered because the FMC Fe-uptake factor is presently being reevaluated [31] and it may, in fact, be unity. When considering that ^{60}Fe/Fe $\approx 2 \times 10^{-15}$ in the FMC ^{60}Fe discovery [11], Table 1 shows that, in both fluence cases, the resulting ^{60}Fe/Fe ratios are well within the capabilities of the Maier-Leibnitz AMS facility across all exposure times τ.

Remaining is the issue of the quantity of core material that would be required to achieve a meaningful result from an AMS measurement. The number of ^{60}Fe atoms per gram of drill core material is given by,

$$N_{60} = C_{\text{SDFe}} \frac{N_A}{M_{\text{Fe}}} \left(\frac{^{60}\text{Fe}}{\text{Fe}} \right) \qquad (5)$$

where all symbols have been previously defined. Inspecting Table 1, let us take ^{60}Fe/Fe $\approx 3.6 \times 10^{-15}$ as our most conservative estimate of this ratio. We then obtain $N_{60} \approx 760/$g of drill core material. The total efficiency ϵ of the AMS facility for ^{60}Fe is known to be $\epsilon \approx 10^{-4}$. Thus, per gram of drill core material, the ^{60}Fe counting estimate should be something on the order of $\epsilon \cdot N_{60} \approx 7.6 \times 10^{-2}$ atoms. A modest ≈ 200 g of sediment material, yielding ≈ 3.8 mg of single-domain iron, would be sufficient for an AMS measurement in search of this signal. Based on these estimates, we conclude there is a plausible prospect for detecting a biogenic signature of this supernova event in magnetofossils.

4. Conclusion

Radioactive ^{60}Fe is a definitive proxy for supernovae and it has been previously discovered in a Pacific Ocean deep-sea FMC [11]. Atmospheric ferric hydroxide nano-grains bearing ^{60}Fe and settling to the deep-ocean should be rapidly consumed by magnetotactic bacteria, resulting in the incorporation of ^{60}Fe into their magnetosomes. Our magnetic remanence measurements of ODP drill core 848 show that magnetofossils dominate the magnetic signature of that portion of the drill core coeval

with the SN time window. Using the half-life corrected ^{60}Fe flux estimates determined in the FMC work of Knie et al. [11] along with the total magnetofossil Fe mass fraction determined from our magnetic remanence results, we have estimated the ^{60}Fe/Fe ratio contained within the magnetofossils of this drill core. Our most pessimistic estimate, ^{60}Fe/Fe $\approx 3.6 \times 10^{-15}$, sits comfortably within the sensitivity capability of the existing AMS facility at the Maier-Leibnitz laboratory. Remaining is an ambitious experimental program dedicated to developing chemical and/or magnetic extraction methods for the iron contained in the SD magnetic fraction of this drill core segment, along with the concomitant AMS measurements to determine if this iron contains supernova ^{60}Fe. Efforts on this front are underway.

Acknowledgements

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